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# Behaviour of concrete in compression and shear under varying strain rates: from rapid to long-term actions

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## Abstract

In the present research, the uniaxial compression behaviour of concrete under different strain rates is investigated. The investigation emphasises the influence of the strain rate on the development of inelastic deformations due to nonlinear creep for high levels of stress (larger than 70% of uniaxial strength). A clear and consistent decrease of the concrete strength for lower strain rates is observed. Acoustic emission measurements clearly confirm the relationship of this phenomenon to the development of concrete micro-cracking with time. An accurate analytical prediction of the strength and remaining deformation capacity has been obtained by applying the affinity hypothesis and the nonlinear creep coefficient previously developed by the authors for constant loading cases.

## 1 Introduction

Some types of reinforced concrete structures are subjected to sustained loads over large periods during their lifetime. This is for example the case of bridges, cut-and-cover tunnels and retaining structures. On the other hand, some concrete structures are designed to carry rapid load actions, as the traffic loads on bridges or impact loads. In the last decades, large research efforts have been devoted on the compressive behaviour of plain concrete as well as on the flexural behaviour of concrete structures accounting for its long-term response (Rüsch 1960, Bazant et al. 1983, Higgins et al. 2013). The influence of sustained loads on the time-dependent deformation of concrete (at serviceability state) is reasonably well known and many approaches exist for its analysis. However, despite some previous works (Sarkhosh 2014), the influence of high sustained loads on the strength of concrete structures needs to be further investigated. In particular, there is a general lack of understanding of the influence of sustained loads and strain rate actions on the shear behaviour of structural concrete members.

Previous research has shown that sustained loads above the elastic threshold of concrete (approximately 40% of its uniaxial compressive strength) imply the development of nonlinear creep strains (Fernández Ruiz et al. 2007). This leads to redistribution of stresses occurring at different strain rates and at different locations of the structural members. A reliable understanding of the behaviour of concrete under different strain rates is yet necessary in order to understand the redistribution of internal stresses in structures as well as their potential damage or even failure under sustained load actions.

With respect to previous approaches to the problem of fatigue under sustained load, Rüsch (1960) is acknowledged as having proposed a rational framework for this phenomenon. He concluded on the existence of a critical threshold for the applied sustained stress to concrete. According to Rüsch (1960), for a sustained load below this threshold, the so-called "creep limit" is reached (maximum value of strain which could be obtained depending on the degree of loading). Above this threshold, concrete would fail under the sustained loading after a given time (again depending on the degree of loading). Several other works have investigated on this topic (Sell 1959, Stockl 1972, Smadi et al. 1982, Iravani et al. 1998), mostly concluding that the minimal load level to reach the sustained load strength of normal strength concrete is around $0.7f_c$ – $0.75f_c$. An extensive literature review of these works is given in (Tasevski et al. 2015).

The final objective of this research is to understand the implications of sustained load and varying rate of loading on the shear behaviour of reinforced concrete members. This investigation, currently on course, comprises an extensive experimental programme on beams with a height of 600 mm and without transverse reinforcement, where the displacement rate is varied between 1 second to failure and appoximatelly 4 months to failure. The main aspects and potential outcomes of this testing programme will also be highlighted and discussed.

## 2 Nonlinear creep in concrete

In uniaxial compression tests at high sustained loads above the creep failure limit as defined by Rüsch(1960), three phases of the development of inelastic creep strains can be clearly distinguished, namely primary, secondary and tertiary creep (see Fig. 1b). From these phases, only tertiary creep occurs if the load level is above the sustained loading failure threshold (see Fig. 1a). According to Fernández Ruiz et al. (2007), primary creep is associated to crack formation, secondary creep is associated to stable crack growth and tertiary creep is associated to uncontrolled crack propagation (see Fig. 1b).

Nowadays it is still a big challenge to predict the development of nonlinear creep strains. Recent concrete design codes (CEN Eurocode 2, *fib* Model Code 2010, SIA 262) propose stress dependent formulas which amplify the linear creep coefficient ($\varphi_{lin}$) in order to take in account for nonlinear creep. However, their applicability remains mostly in the serviceability limit state domain ($\sigma < 0.6f_c$). Fernández Ruiz et al. (2007) proposed a formula which corrects the linear creep coefficient $\varphi_{lin}$ as follows:

$$\varphi_{nl}\left(t, t_0, \frac{\sigma}{f_c}\right) = \eta\left(\frac{\sigma}{f_c}\right) \cdot \varphi_{lin}(t, t_0) \tag{1}$$

$$\eta\left(\frac{\sigma}{f_c}\right) = 1 + 2\left(\frac{\sigma}{f_c}\right)^4 \tag{2}$$

The correction factor was calibrated on the basis of tests with load levels up to $0.7f_c$. This factor was also demonstarated (Fernández Ruiz et al. 2007) to be applicable to failures under sustained loads (for stress levels above $0.7f_c$) provided that the tertiary creep is assumed as an additional 1/3 of the total inelastic strain (the so-called “affinity hypothesis”, see Fig. 1b).

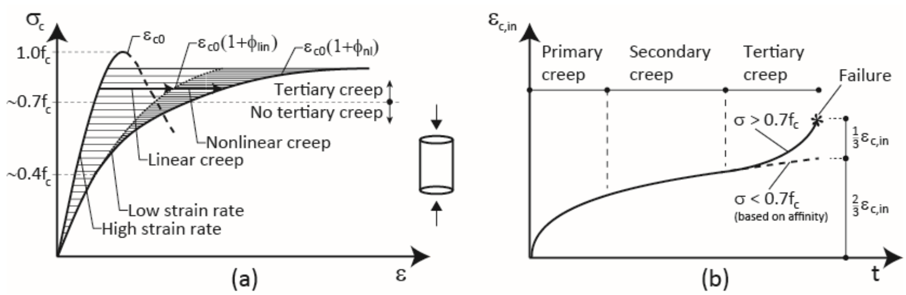


Fig. 1 Generalised stress-strain behaviour for a high and a low strain rate compressive test (left). Inelastic creep strains for the three creep phases (right). Adapted from Fernández Ruiz et al. (2007).

The objective of the current research project is to investigate the physical origin of the phenomenon of creep failure and to quantify the development of nonlinear creep strains for different stress levels and different strain rates. This paper extends a previous work of the authors (Tasevski et al. 2015) where an analogy was demonstrated amongst the concrete behaviour under sustained loads and under varying strain rates.

## 3 Experimental investigation

### 3.1 Test programme and main results

The uniaxial compressive behaviour of concrete under different strain rates has been investigated by means of cylindrical specimens Ø×*h* = 160×320 mm. The tests were performed using a Schenck Hydroplus servo-hydraulic testing machine with capacity of 2.5 MN and a custom-made steel frame which enhances the stiffness of the test setup (Fernández Ruiz et al. 2007). The climatic room where the tests are performed has controlled temperature (21±0.5 °C) and relative humidity (52±3 %). The longitudinal strain $\varepsilon_3$ is measured with three surface displacement transducers arranged radially on two steel rings at a distance of 250 mm. The transversal strain $\varepsilon_1$ is measured with a steel ribbon dilatometer equipped with a linear variable differential transformer (LVDT).

The experimental programme of uniaxial compression covered strain rates ranging from $2 \cdot 10^{0}$ [‰/s] to $2 \cdot 10^{-6}$ [‰/s] (time to failure from 1 second to ca. 12 days). The mean 28-day compressive cylinder strength was 30.6 MPa (tested with the reference strain rate of $2 \cdot 10^{-2}$ [‰/s], corresponding to 100 seconds until failure). The concrete age at testing was about 10 months. The results of the experimental programme are presented in detail in (Tasevski et al. 2015); the most important results are summarized in Fig. 2 and Table 1:

Table 1 Test results from uniaxial compression tests with varying strain rates

| $\dot{\varepsilon}_{nominal}$ [‰·s$^{-1}$] | $t_{fail,nominal}$ [s] | $f_c$ [MPa] | $\varepsilon_{3u}$ [‰] | $t_{fail}$ [s] | $t_{fail}$ [-] | $\dot{\varepsilon}$ [‰·s$^{-1}$] |
|---|---|---|---|---|---|---|
| $2 \cdot 10^{0}$ | 1 | 41.8 | 1.88 | 0.85 | 1 sec | $2.2 \cdot 10^{0}$ |
| $2 \cdot 10^{-1}$ | 10 | 40.5 | 2.03 | 9.26 | 10 sec | $2.2 \cdot 10^{-1}$ |
| $2 \cdot 10^{-2}$ | 100 | 38.7 | 2.01 | 98.6 | 100 sec | $2.0 \cdot 10^{-2}$ |
| $2 \cdot 10^{-3}$ | 1’000 | 37.8 | 2.07 | 1’010 | 17 min | $2.0 \cdot 10^{-3}$ |
| $2 \cdot 10^{-4}$ | 10’000 | 37.1 | 2.36 | 11’800 | 3h 17 min | $2.0 \cdot 10^{-4}$ |
| $2 \cdot 10^{-5}$ | 100’000 | 36.5 | 2.61 | 113’000 | 1d 7h | $2.3 \cdot 10^{-5}$ |
| $2 \cdot 10^{-6}$ | 1’000’000 | 34.3 | 2.75 | 1’050’000 | 12d 4h | $2.6 \cdot 10^{-6}$ |

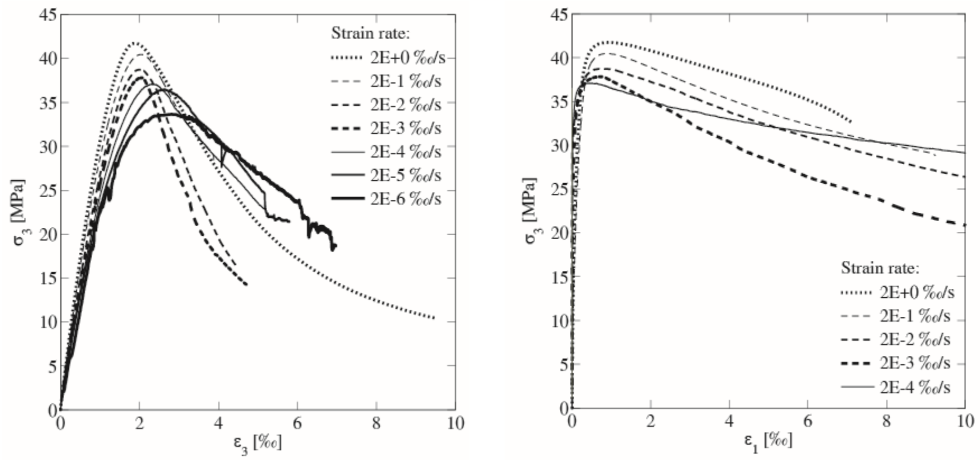


Fig. 2 Uniaxial compression test results for longitudinal strains (left) and transversal strains (right). Adapted from Tasevski et al. (2015).

The development of micro-cracking during the tests with strain rates of $2 \cdot 10^{-2}$ [‰/s] and $2 \cdot 10^{-4}$ [‰/s] has been tracked by means of acoustic emission measurements. The details about the acoustic emission setup and parameters are given in (Tasevski et al. 2015).

## 3.2 Discussion of test results

The experimental results for the investigated strain rates reveal a reduction of concrete strength of about 13% between the slow test of 12 days and the reference test of 100 seconds (refer to Fig. 2). At the same time the ultimate longitudinal strain shows an increase for decreasing strain rate. The strain rate seems to play an important influence also on the post-peak brittleness which decreases for decreasing strain rate.

On the specimens, detailed measurements were performed by using the Acoustic Emission (AE) technology. The results of these measurements are expressed in terms of cumulative damage curves (Fig. 3 right). The cumulative damage is quantified as following:

Cumulative damage = CumΣ(Hits · Amplitude) / CumΣ(Hits)

According to the cumulative damage curve, the onset of micro-cracking can be clearly detected at stress levels between around $0.4f_c - 0.45f_c$, which corresponds to the elastic limit of uniaxial compressive behaviour. Another phenomenon which can be observed in the cumulative damage curve is the onset of tertiary creep. It is clearly visible that the tertiary creep phase starts already at lower load levels for tests with decreasing strain rates. This methodology allows to determine the amount of damage before and after the onset of tertiary creep. Consequently, a clear distinction between the secondary and tertiary creep rates can be concluded. Such analyses seem a promising manner to confirm the suitability of the assumption made by Fernández Ruiz et al. (2007) regarding the applicability of the affinity hypothesis.

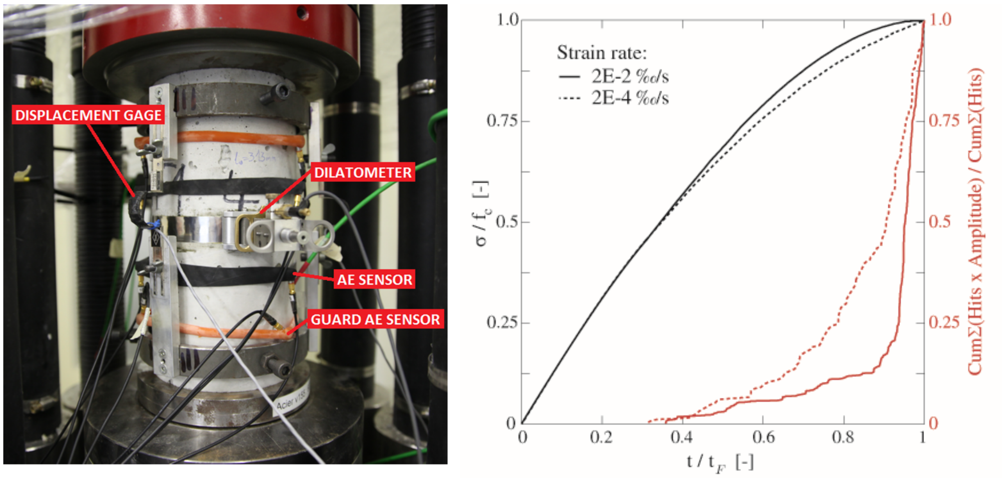


Fig. 3 Uniaxial compression test setup (left). Cumulative cracking for different strain rates measured with acoustic emission (right).

A further test series on specimens loaded under varying strain rates is still in progress, in order to confirm the observed results. The development of micro-cracking is systematically tracked by acoustic emission measurements. The test series is accompanied with shrinkage and linear creep tests in order to be able to quantify for the nonlinear creep portion.

## 4 Prediction of test results

This section presents the prediction of the creep strain development in uniaxial compression tests with varying strain rates performed by Rüsch (1960) as well as by Tasevski et al. (2015). In order to take in account for the exact stress history, the strain development has been calculated by means of the superposition principle (corrected with the assumption of the affinity hypothesis). This is performed by applying the following formula:

$$\varepsilon(t_i) = \frac{\sigma(t_{0,i})}{E_c(t_i)} + \sum_{j=1}^{j=i-1} \left( \frac{\sigma(t_{0,j})}{E_c(t_j)} \cdot \varphi_{nl}(t_i, t_{0,j}) - \frac{\sigma(t_{0,j})}{E_c(t_{j+1})} \cdot \varphi_{nl}(t_i, t_{0,j+1}) \right) \quad (3)$$

where $\varphi_{nl} = \eta \cdot \varphi_{lin}$ and $\eta$ (refer to Eq. (2)) is the stress dependent correction formula proposed by Fernández Ruz et al. (2007). Fig. 4 presents the comparison of experimental and analytical results of the tests performed by Rüsch (1960) and Tasevski et al. (2015).

The analytical results prove the applicability of the assumption of Fernández Ruiz et al. (2007) that the inelastic creep strain due to unstable crack growth consists of approximately 1/3 of the total inelastic creep strain caused by micro-cracking (the assumption of the affinity hypothesis). However, further AE measurements are needed to quantify for the exact portion of tertiary creep strains if the creep failure occurs at different load levels. As a consequence, the assumption is currently under revision.

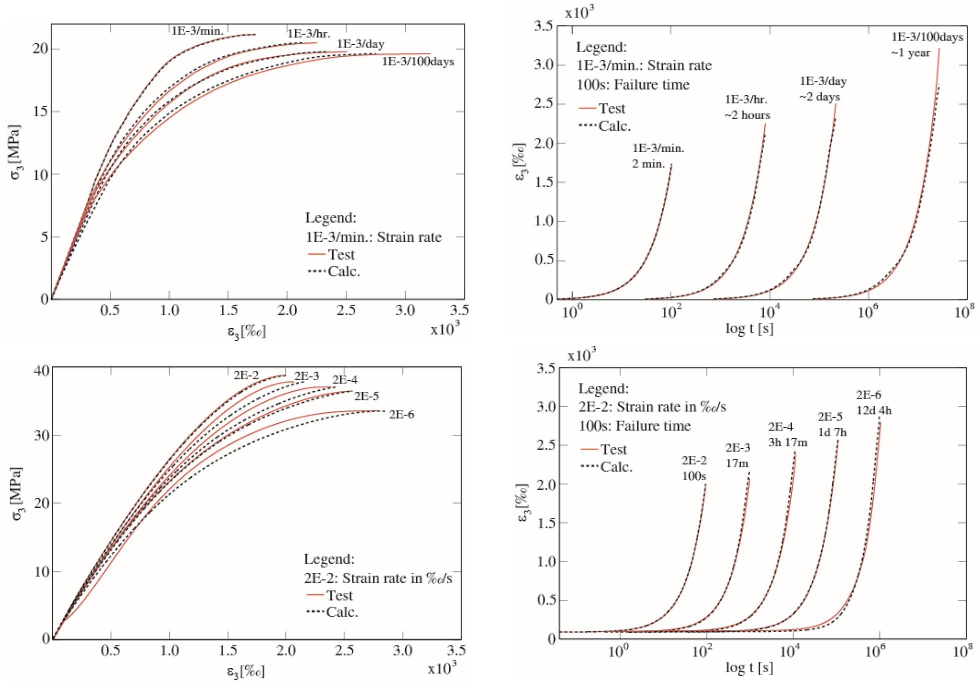


Fig. 4 Experimental and analytical results for strain rate tests performed by (Rüsch 1960) (up) and (Tasevski et al. 2015) (down).

## 5 Ongoing experiments on shear beams

Scanty experimental and theoretical studies have so far investigated the possible effect of sustained loads and strain rates on the shear strength of beams and one-way slabs (Sarkhosh et al. 2013, Sarkhosh 2014). In order to develop suitable shear design methods accounting for the long-term response of concrete and to provide experimental data in this field, two experimental series on shear critical beams are being performed within this research. The specimens have rectangular cross section (600 mm height) and a flexural reinforcement ratio $\rho = 1.33$ %. The shear span to effective depth ratio of the first series is $a/d = 3.5$, whereas it is 1.0 for the second. The load is applied under controlled displacement, with a servo-hydraulic jack with capacity of 2 MN. The displacement rate is varied between 1 second to failure and appoximatelly 4 months to failure. The main aim of this programme is to investigate:

- the time-dependent development of the failure mechanism and the crack pattern as well as the analogies with the uniaxial behaviour of concrete,
- the time-dependent contribution of different shear transfer actions and the redistribution of stresses.

Fig. 5 gives an overview over the test setup for shear critical beams.

## 6 Conclusion and outlook

This paper presents the main experimental and theoretical lines that are being followed on an ongoing research on the long-term behaviour and strength of concrete structures. The research focuses both on the material behaviour and on the structural behaviour.

The experimental results on the behaviour of concrete under varying strain rate in uniaxial compression tests show a progressive development of nonlinear creep strains for decreasing strain rates. As a consequence of this, the concrete compressive strength decreases. The onset of microcracking has been found to be at load levels of around $0.4f_c$ - $0.45f_c$ (which is consistent to the elastic limit) by means of acoustic emission measurements. It has also been shown that the nonlinear creep factor proposed by Fernández Ruiz et al. (2007) accurately predicts the nonlinear creep strain development even for load levels above $0.7f_c$. However, review of the main assumption of this formula is needed in order to account for the exact fraction of tertiary creep strain at creep failure at differend load levels.

The material tests will be completed with an experimental programme on full-scale beams failing under long-term actions. The main aim of this second experimental programme is to advance on the knowledge of the phenomenon of shear failures under sustained load and varying rate of loading.

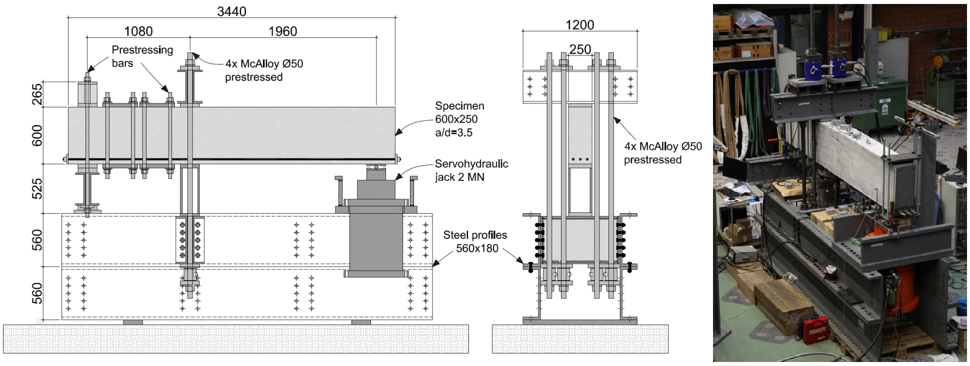


Fig. 5 Test setup for shear critical beams.

## Aknowledgement

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